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Abstract

Tile drainage systems are sometimes not sufficient to provide favorable unsaturated conditions in the rootzone. These drainage systems then need to be supplemented with an additional high conductivity material in the trenches above the tiles or by implementing mole drainage. The HYDRUS (2D/3D) model was used to evaluate the impact of such additional measures for heavy clay soil. Three types of drainage systems were simulated: i) tile drains, ii) tile drains with gravel trenches, and iii) tile drains with gravel trenches and mole drains, using either two-dimensional (the former two systems) or three-dimensional (the latter one) transport domains. Three scenarios were considered to test the efficiency of each system: i) time to drain an initially saturated system, ii) high intensity rainfall, and iii) a real case scenario. Different horizontal spacings between tile drains with or without gravel trenches were also compared with the system which included mole drainage. The results showed that the drainage system that included mole drains and gravel trenches was the most efficient. This system provided the largest drainage rate, was the first to reach steady-state in the time to drain scenario, and also efficiently reduced surface runoff. Adding mole drains to a system with tile drains and gravel trenches resulted in a large reduction of surface runoff (75%). Simulations showed that the spacing of tile drains with or without gravel trenches would have to be 40% or 55% smaller, respectively, in order to reproduce the same water table levels as those observed for the drainage system with mole drains. Therefore, introducing mole drains in drainage systems is an efficient practice for reducing waterlogging and runoff.

Keywords: Tile drainage; Mole drainage; Numerical simulation; Heavy soil; Three-dimensional modeling

1. Introduction

Soil drainage systems aim at limiting saturated conditions in the soil profile that can arise due to hydrological processes from above (downward water percolation) and from below (elevated groundwater). The main goal of drainage systems is to remove excess water and maintain favorable unsaturated conditions in the rootzone. The most common agricultural drainage system consists of perforated PVC tile drains installed in soil at various spacing's and depths, depending on soil hydraulic properties, climatic conditions, and cultivated crops. When designing drainage systems, it is crucial to increase the hydraulic functioning of the entire system. These systems are mostly installed in soils with high clay content, i.e., heavy soils with very low hydraulic permeability (Tuli et al., 2005). In such soils, subsurface drainage systems can substantially reduce surface runoff, shorten periods of surface ponding, and lower water table (Konyha et al., 1992; Skaggs et al., 1994). Under certain conditions, including high groundwater table, large and intensive precipitation, and heavy-textured soils, the installation of tile drains may not be sufficient to provide favorable conditions for growing crops. Additional measures may then be needed, such as using a backfill material (gravel) with a high hydraulic conductivity above tile drains or performing *mole drainage*. The presence of a gravel layer above tile drains up to the tilled layer may increase the efficiency of the entire system by promoting by-pass flow of water from the tilled layer directly into the drains. Mole drains are closely-spaced unlined channels of limited duration that are formed in clay subsoil using a ripper blade with a cylindrical foot, often with an expander, which helps to compact and stabilize the channel walls. Mole drainage has been recommended for heavy soils with low permeability, which would otherwise require a small drain spacing (Hudson et al., 1962). During the construction of the mole channels the foot and expander create a 'leg slot' directly above the mole as well as fissures in the soil upwards from the mole towards the plough layer. These cracks and fissures can promote preferential flow towards mole drains (Leeds-Harrison et al., 1982). Mole drains are intended to improve lateral flow to tile drains and are usually used only in soils with a high clay content (>35%). If established properly and under the right conditions, they may still be operating after five years (Harris, 1984). Tile and mole drains are nonconductive under unsaturated conditions because positive pressure must occur before water can start flowing into them (Stormont and Zhou, 2005).

In recent years, numerical models have been developed to simulate water flow in tile-drained soils. One-dimensional (1D) models (e.g. MACRO, Larsbo and Jarvis, 2003) use an approximate analytical solution of Darcy’s equation to account for water loss through the drainage system (e.g., Hooghout, Ernst, or Boussinesq’s equations), while two- or three-dimensional (2D or 3D) models (e.g. HYDRUS (2D/3D), Šimůnek et al., 2006) use the Richards’ equation to explicitly model the dynamics of the water table. In 1D models, the flow to tile drains is implemented as a sink term in the mass balance equation. The Houghoudt's equation is based on the Dupuit-Forschheimer assumptions with corrections for convergence of radial flow near the tiles. When combining the Houghoudt's equation (for the saturated zone) with the Richards equation (for the unsaturated zone), the Houghoudt's equation gives instant lateral fluxes to tile drains, while the Richards equation gives transient fluxes in the unsaturated zone, leading to a rise or drop of the water table. An example of such model is DrainMod, which has been used in many applications. For example, Skaggs et al. (2012) used DrainMod to simulate water flow in a subsurface-drained agricultural field in eastern North Carolina. The performance statistics indicated that the model with calibrated input data accurately predicted daily water table depths, daily drainage rates, and monthly drainage volumes. Singh et al. (2006) calibrated and tested DrainMod on two types of soils in Iowa and used it to simulate the impacts of different designs of subsurface drainage systems. Simulation results suggested that a drainage system designed for a drainage intensity of 4.6 mm d^{-1} with a drain depth of 1.05 m and a drain spacing of 25 m was sufficient to maximize crop production under the prevailing local agricultural conditions.

Water flow and solute transport to tile drains has been also evaluated using the HYDRUS family of codes (Šimůnek et al., 2008). For example, the HYDRUS-2D software package was used by De Vos et al. (2000, 2002) to simulate nitrate transport in a tile-drained layered silt loam soil in a reclaimed Dutch polder, or by Castanheira and Serralheiro (2010) to evaluate the impact of mole drains on salinity of a vertisol under irrigation.

Numerical modeling of drainage systems involving both tile and mole drains is much more limited. Snow et al. (2007) used the APSIM-SWIM model to predict drainage rates and runoff in a mole-tile drained silty loam soil of New Zealand. There was an excellent agreement between simulated and measured drainage, as well as a reasonable agreement between measured and simulated cumulative surface runoff. Armstrong et al. (2000) performed a modeling study on a macroporous clay soil with mole and tile drains, in which they compared four "preferential flow" models (MACRO, CRACK-NP, SIMULAT and PLM) in their ability to simulate isoproturon leaching. MACRO model gave the best results, although globally the simulations showed the difficulty of deriving adequate parameters, even where relatively complete soil physical data were available. A similar study was performed by Besien et al. (1997) on a structured heavy clay soil with tile (0.75 m depth and 50 m spacing) and mole drains (0.5 m depth and 3 m spacing) in which the MACRO model was calibrated and used to investigate the leaching of isoproturon. Madvar et al. (2007) used the SEEP/W model to simulate the hydraulic performance of mole and tile drains in heavy-textured soil. Based on their numerical study the combination of mole and tile drains resulted in economical and hydraulic improvement of the agricultural system.

Most of modeling studies considered water flow in one- or two-dimensional soil profiles, either taking into account only tile drainage without mole drainage or mole drainage without tile drainage (e.g., Castanheira and Serralheiro, 2010), but not both in a fully three-dimensional system. This is mainly because mole drains, being installed in a perpendicular direction to tile drains, make the entire system three-dimensional. Since we could not identify any study that simulated water flow in systems with tile and mole drains as a three-dimensional problem, we conducted 3D numerical experiments to evaluate the performance of these systems. In our numerical simulations we considered environmental conditions that are typical for the eastern part of Croatia. Hydromorphic soils in Croatia cover an area of 1,618,500 ha, which is approximately one third (29%) of the total area occupied by agricultural soils (Husnjak, 2007). Subsurface tile drainage systems are installed on 161,530 ha (Petošić et al, 2004), with mole drainage often used to improve drainage efficiency.

The main objective of this paper was to numerically evaluate the performance of different subsurface drainage systems of increasing complexity in hydromorphic soils using a three-dimensional model that can explicitly account for any drainage system. (i) The simplest system to be considered consists of a layered soil profile with parallel tile drains. Such system can be simulated using a two-dimensional simulation domain that is perpendicular to tile drains. (ii) In the second set of simulations it is assumed that a backfill material (gravel) of higher hydraulic conductivity than the original soil is placed above the drains. Such system can also be evaluated assuming a two-dimensional simulation domain perpendicular to drains. (iii) Finally, the most complex system consists of tile drains with backfilled gravel above drains, combined with perpendicular mole drains. Such system has to be analyzed using a fully three-dimensional flow model.

2. Materials and methods

2.1. Theory

Subsurface water flow in the unsaturated and saturated zones is governed by the mass balance equation and the Darcy-Buckingham's law:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial J_{wi}}{\partial \boldsymbol{x_i}} - S(h) \qquad (1)$$

$$J_{wi} = -K(h)K_{\boldsymbol{ij}}^{A}\frac{\partial H}{\partial \boldsymbol{x_j}} = -K(h)\left(K_{\boldsymbol{ij}}^{A}\frac{\partial h}{\partial \boldsymbol{x_j}} + K_{\boldsymbol{ij}}^{A}\right) \qquad (2)$$

respectively, where θ is the volumetric water content [L^3L^{-3}], J_{wi} is Darcy's flux [LT^{-1}] in the i-th direction, S is a sink/source term [T^{-1}], $K(h)$ is the saturated/unsaturated soil hydraulic conductivity function [LT^{-1}], $K_{ij}{}^A$ are the components of the dimensionless anisotropy tensor for hydraulic conductivity K^A [-], H is the total hydraulic head [L] defined as the sum of the pressure head and the gravitational head, $H = h$+z, x_i are the spatial coordinates [L], with x and y being horizontal coordinates and z the vertical coordinate directed upwards, and t is time [T]. The governing flow equation for these conditions, resulting from combining (1) and (2), is given by the following modified form of the Richards' equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial \boldsymbol{x_i}}\left[K\left(K_{\boldsymbol{ij}}^A \frac{\partial h}{\partial \boldsymbol{x_j}} + K_{\boldsymbol{ij}}^A\right)\right] - S \qquad (3)$$

The unsaturated hydraulic conductivity function $K(h)$ is given by:

$$K(h, x, y, z)=K_s(x, y, z)K_r(h, x, y, z) \qquad (4)$$

where K_r is the relative hydraulic conductivity [-] and K_s is the saturated hydraulic conductivity [LT^{-1}].

Soil hydraulic functions were described using the van Genuchten-Mualem model (van Genuchten, 1980), which is defined as follows:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{(1+|\alpha h|^n)^m} \qquad \text{for } h<0 \qquad (5)$$

$$\theta(h) = \theta_s \qquad \text{for } h\geq 0$$

$$K(h) = K_s S_e^l (1-(1-S_e^{\frac{1}{m}})^m)^2 \qquad (6)$$

$$S_e = \frac{\theta-\theta_r}{\theta_s-\theta_r} \qquad (7)$$

$$m = 1 - \frac{1}{n}; \quad n>1 \qquad (8)$$

where θ_r and θ_s denote residual and saturated volumetric water contents [L^3L^{-3}], respectively; S_e is the effective saturation [-], α [L^{-1}], and n [-] are retention curve shape factors, and l is a pore connectivity parameter [-]. A numerical model for simulating water flow and solute transport in two- and three-dimensional transport domains, HYDRUS (2D/3D) (Šimůnek et al., 2006), was used it this study.

2.2. Numerical Experiments and Input Data

2.2.1. Soil Hydraulic Properties

Numerical experiments were set up for a Eutric Haplic Calcaric Siltic Gleysol (horizons: Ap; Bg; Cr; Cg), which is located in eastern Croatia (45°09' N and 18°42' E). Disturbed soil samples were taken from each horizon and particle size distribution was determined using the pipette method (Gee and Or, 2002). Undisturbed soil samples (100 cm^3) were used to measure bulk density and soil hydraulic properties. The saturated hydraulic conductivity, K_s, was measured using the constant head method (Klute and Dirksen, 1986). The saturated water content, θ_s, was measured using the ISO 11274:1998 sandbox method (Clement, 1966). Data points of the soil water retention curve were measured using the pressure plate apparatus (Dane and Hopmans, 2002) for applied pressures of 3, 10, 33, 100, 625, and 1500 kPa. While the saturated water content, θ_s, was measured, the remaining parameters of the soil water retention curve (5) (θ_r, α, and n) were optimized using the RETC software (van Genuchten et al., 1991) by fitting measured data. R^2 values for soil water retention curve fitting were in range from 0.91 to 0.99. The pore connectivity parameter, l, was assumed to be equal to an average value for many soils (l=0.5) (Mualem, 1976). The hydraulic properties of the material that was assumed to be backfilled into the tile trenches were taken from the soil catalog of Carsel and Parrish (1988) for sand, with an increased K_s value to imitate the hydraulic properties of gravel (Table 1). As only one seepage face boundary condition could be considered in HYDRUS (2D/3D), mole drains were simulated as a gravel material with hydraulic properties identical to those of the material used for tile trenches.

2.2.2. Drainage systems

Three different drainage systems were evaluated in our numerical simulations. The simplest system (System 1) consisted of parallel tile drains and no other additional measures (denoted below in graphs and tables as “tile”). In simulations for System 2 (denoted as “tile_gravel”), it was assumed that a backfill material (gravel) of higher hydraulic conductivity was placed above drains. Finally, the most complex system (System 3) consisted of tile drains with a backfilled gravel above drains combined with perpendicular mole drains (denoted as “tile_gravel_mole”). Fig. 1 shows a schematic of the simulated drainage systems. System 1 and 2 were evaluated assuming a two-dimensional transport domain perpendicular to tile drains (Fig. 1a), while System 3 needed a fully three-dimensional water flow model (Fig. 1b).

2.2.3. Transport Domain

Because of the symmetry of water flow between two parallel tile drains, it was possible to consider only a half domain between two tile drains. A two-dimensional transport domain for Systems 1 and 2 (Fig. 1a) thus had a width of 750 cm (tile drain spacing was assumed to be 15 m) and a height of 200 cm. The 8 cm diameter tile drain, which was located on the left side of the transport domain, was assumed to be centered at a depth of 96 cm from the bottom of the soil profile. The soil profile was divided into 4 soil horizons (Table 1) based on a soil survey of the area. In simulations of System 2, an additional vertical layer of gravel, representing a backfill material (material 5; Table 1), was considered. The three-dimensional transport domain for System 3 (Fig. 1b) with tile and mole drains and a backfill material above the tile drains had the same first two dimensions as the two-dimensional transport domains, i.e., a width of 750 cm and a depth of 200 cm. The third dimension, perpendicular to tile drains, was equal to 100 cm (mole drain spacing was assumed to be 2 m). The mole drain, which was perpendicular to tile drains, was located at the front of the three-dimensional transport domain (Fig. 1b) and was assumed to have a diameter of 6.5 cm, an inclination of 0.5%, and was 40 cm deep (from the soil surface) above the tile drain.

2.3.4. Simulated scenarios

Numerical simulations were carried out for each drainage system for three different scenarios with different initial and boundary conditions. In Scenario 1, a "time to drain" scenario was used to compare the drainage response of the three simulated systems, i.e., tile drains, tile drains with gravel trenches, and tile drains with gravel trenches and mole drains, starting from wet soil conditions. The initial pressure head was assumed to be at equilibrium conditions with a positive pressure head of 175 cm at the bottom of the transport domain which left the first 25 cm (corresponding to the tilled layer) unsaturated. No flow boundary condition was considered for all boundaries except for the small semicircle on the left of the transport domain which represented the tile drain (Fig. 1a). A seepage face boundary condition was used to represent the tile drain. Simulation time was equal to 2,400 hours (100 days). However, as there was still some limited outflow after 2,400 hours, the time when drainage was assumed to stop was defined as the time when the drainage rate decreased below 0.001 mm h^{-1}. Simulations for Systems 1 and 2 were also performed in 3D to check if the results were identical to those provided by 2D modeling.

In the "rainfall” scenario (scenario 2), the initial conditions were set up as the pressure head distribution from the end of the first scenario (steady state conditions), and a rainfall event (with an intensity of 2 mm/h and a duration set up to get a total of either 50 mm, 100 mm, or

150 mm) was applied starting at the first day of simulation. In addition to a seepage face boundary condition representing a tile drain, an atmospheric boundary condition was applied at the top of the transport domain to include rainfall. Evaporation was neglected in this scenario.

In the "real case" scenario (scenario 3), 4-year simulations (2009-2012) were performed with meteorological data collected at the Gradište station (45°09' N and 18°42' E) using the same initial conditions as in scenario 2. An atmospheric boundary condition was applied at the top of the transport domain using evapotranspiration values calculated by the Penman-Monteith approach (Monteith, 1981). Transpiration was calculated formaize (*Zea Mays* L., 2009, 2010, 2012) and barley (*Hordeum vulgare* L., 2011) which were grown at the actual location. Again, a seepage face boundary condition was selected to represent the tile drain.

3. Results and discussion

3.1. "Time to drain" scenario

To evaluate the specific drainage response of each of the three drainage systems, a "time to drain" scenario was performed. The ending time of drainage was reached at 681 h (28.4 days) for the tile system, 594 h (24.7 days) for the tile_gravel_system, and 506 h (21.1 days) for the tile_gravel_mole system. The value corresponding to 90% of the final drainage volume from each system was selected as the time when a quasi steady-state condition was reached. According to this criterion, the systems reached quasi steady-state after cumulated outflow amounts of 4.86 mm, 6.57 mm, 9.18 mm for the tile, tile_gravel, and tile_gravel_mole systems, which corresponded to days 11, 7.1, and 6, respectively (Fig. 2). The difference in time response of the three systems may have a large influence on the crop root system, i.e., the faster the soil is drained the less consequences on the crop root system and yield can be expected (Oosterbaan 1991). The soil horizons had a relatively low permeability and, in the absence of a highly conductive layer, the drainage is very slow. When a gravel trench above the tile is added, the time response is faster (Fig. 2) since the trench is filled up with a material that has a high saturated hydraulic conductivity. The response of the system with moles is fastest since it includes both the trench and the mole drain constructed from the same highly conductive material as the trenches. Since the domain was initially saturated well above the mole drain depth, the response of the system is increasing in the order tile < tile_gravel < tile_gravel_mole.

In addition to the time response of each system, a large difference in the cumulative amount of drainage was found. This difference is due to the substitution of soil materials having different water retention properties within the simulation domain. In System 2, parts of the volumes of materials 1, 2, and 3 are replaced by material 5 to represent the gravel trench. In System 3, in addition to the trench, a part of material 2 is replaced by material 5 to represent the mole drain. The difference in water storage between System 1 and System 2 is 1.86 mm and 4.86 mm between System 1 and 3. Material 5 and materials 1, 2, and 3 have very different water retention properties, which explain the different cumulative outflows (Table 2). Inserting a gravel trench above the tile drain increased outflow by 1.86 mm, 90% of it coming from the water initially stored in the trench itself. Adding a mole drain (System 3) further increases the outflow by 3 mm, with more than half of it coming from the gravel material representing the mole drain. From these results one can already expect a significant effect of the mole drain on the recession of the water table.

Fig. 3 shows the simulated cross sections of all three systems during the first 24 hours. The results are displayed after 2 and 24 hours. Pressure head values are lower in the tile_gravel system than in the tile system and the lowest in the tile_gravel_mole system. After 2 h of drainage, the influence of the trench in System 2 is limited to the right side of the domain while in System 3 the effect is expanding more to the left side because of the presence of the mole drain. After 24 h, there is a large drop in the water table depth for all three systems in the order (high to low) tile > tile_gravel > tile_gravel_mole. The mean pressure head after 24 hours in the domain above the tile depth (from the surface down to 100 cm) was -75 cm, -78 cm, and -84 cm for the tile, tile_gravel, and tile_gravel_mole system, respectively. These results indicate the higher efficiency of the tile_gravel_mole system in reducing the water table height compared to the tile_gravel system.

3.2. High intensity rainfall scenario

High intensity rainfall events with an intensity of 2 mm per hour and various durations, to get total amounts of 50 mm, 100 mm, or 150 mm, were applied in the second scenario. The initial condition was set equal to the final pressure head distribution at the end of the first scenario, i.e., the surface pressure head was -108 cm and the bottom pressure head was 92 cm on the right side of the domain. The cumulative outflow increased with the rainfall intensity in all three systems (Fig. 4). In this scenario, the trench and mole drain were not initially saturated as in the previous scenario, which led to the slower response time at the beginning of the experiment. The gravel material (representing the trench and mole) was not initially saturated and the time needed for its saturation induced a delay in the system response, which can be best seen for the tile_gravel_mole system during the first 4 hours (Fig. 4). There is no outflow during the first 4 hours in System 3 since the mole drain needs to be saturated to trigger drainage. The tile system without a gravel layer became almost instantaneously saturated since the rest of the domain had a very low permeability (5 mm h^{-1}).

The low permeability of the soil promotes runoff during high intensity rainfalls. In Fig. 5, the total amount of surface runoff is presented for each system. One can see that the cumulative amount of runoff increases according to rainfall intensity, while the opposite was found for cumulative outflow (Fig. 4). The largest runoff occurs in the tile system, then in the tile_gravel system, and the smallest in the tile_gravel_mole system. The mole drain was very efficient in reducing surface runoff. These results are in agreement with several studies, in which authors found that artificial drainage increases the amount of infiltrating water and reduces runoff (e.g., Bengtson et al., 1995).

Mass balance information for all three system and three rainfall events is shown in Table 3. Table 3 shows that the effectiveness of mole drainage in reducing surface runoff is not only due to a better efficiency in promoting drainage outflow, but also due to a better capacity for water storage than for the other two drainage systems.

3.3. Real case scenario

For the real case scenario, agroecological conditions that correspond to East Croatia were taken into account to be able to explain the behavior of each system in real field conditions. Fig. 6a shows the cumulative outflow during 2009-2012 period. At the beginning, one can see that the order of drainage relative to cumulative outflow is a bit different from what was found in first two scenarios in which the tile_gravel_mole system had the largest outflow. This effect is due to the small rainfall amounts at the beginning of the simulated time period which were drained by the tile_gravel system, but not by the tile_gravel_mole system, because mole drains did not become saturated enough to trigger outflow. Long term simulations showed the opposite effect on the 1st of June 2010 when a high intensity rainfall event (72.8 mm) saturated mole drains and promoted a large outflow from the tile_gravel_mole system, while in the same time other two systems generated low outflow and large surface runoff (Fig. 6b). Adding gravel in the trench above a drain resulted in small decrease of surface runoff by (1%) However, inserting a mole drain into the system decreased the runoff by an additional 75%. The tile drain system with gravel and mole drains effectively reduced surface runoff in real field conditions. In such situation, the tile_gravel system cannot conduct such large amounts of water as the system with moles, which leads to waterlogging conditions at the surface or the presence of a high water table.

3.4. Drain spacing

Finally, simulations with different tile drain spacings were performed in order to compare the water table variations for each system and to try to obtain, either with only tile drains or tile drains with backfilled trenches, the same water table level as for System 3. The simulation set up e.g., initial and boundary conditions was taken from the "time to drain" scenario. The tile with gravel trenches and mole system had the same spacing of 15 m as in above studied scenarios. The tile and tile_gravel systems were set up with various spacings from 6 to 12 m. Figs. 7a and 7b show the water table elevation during 96 h in the middle between two tile drains for the three systems (numbers 6, 7, 8, 9, 10, 12 corresponds to the drain spacing in meters). At the beginning, there is a rapid decrease in water table depths in all three systems, clearly visible during the first 24 hours. After that, the decrease is smaller and starts to stabilize as time approaches the end of simulation. The tile_gravel system was more efficient than the tile system at each spacing in lowering the water table (by ~2 cm). To reproduce the same water table level after 96 h (-100.2 cm) as in the tile_gravel_mole system, one would need to lower the spacing of the tile_gravel system to 9 m, or to 7 m if the system without gravel is used. System 1 and 2 with a 6-m spacing were able to lower the water table more efficiently than System 3 with a 15-m tile drain spacing and a 2-m mole drain spacing. However, a system with such small tile drain spacing is not economically sustainable. A small tile drain spacing is mostly used only in golf course construction or in civil engineering. Since the construction of mole drains requires only a simple equipment (i.e., a special kind of plough) (Hopkins 2002), this system could significantly lower the overall cost of the drainage system.

4. Conclusions

Numerical experiments have been performed for three different drainage systems: i) tile drains, ii) tile drains with gravel trenches, and iii) tile drains with gravel trenches and mole drains. The tile drain system showed in all scenarios the slowest outflow response and the smallest cumulative outflow. When compared with the other two systems, the drainage system with tile drains, gravel trenches, and mole drains provides the largest efficiency. Under real case scenario, the system with tile drains and gravel trenches had the fastest reaction time and provided drainage outflow for small intensity rainfalls. However, the system with tile drains, gravel trenches and mole drains was able to provide larger outflow during higher intensity rainfall (>15 mm). Adding mole drains to a system with tile drains and gravel trenches resulted in a very large reduction of surface runoff (75%), which can have a very important effect during high intensity rainfalls. Since the use of the drainage systems with mole drains is still limited to special agro ecological conditions, there is only limited extensive field data available which allow to test fully three-dimensional simulations of these particular drainage systems. Research needs to be expanded through field trials in order to have more information on water flow dynamics in such complex systems.

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Table 1. van Genuchten soil hydraulic parameters for all horizons of the soil profile used in the numerical simulations.

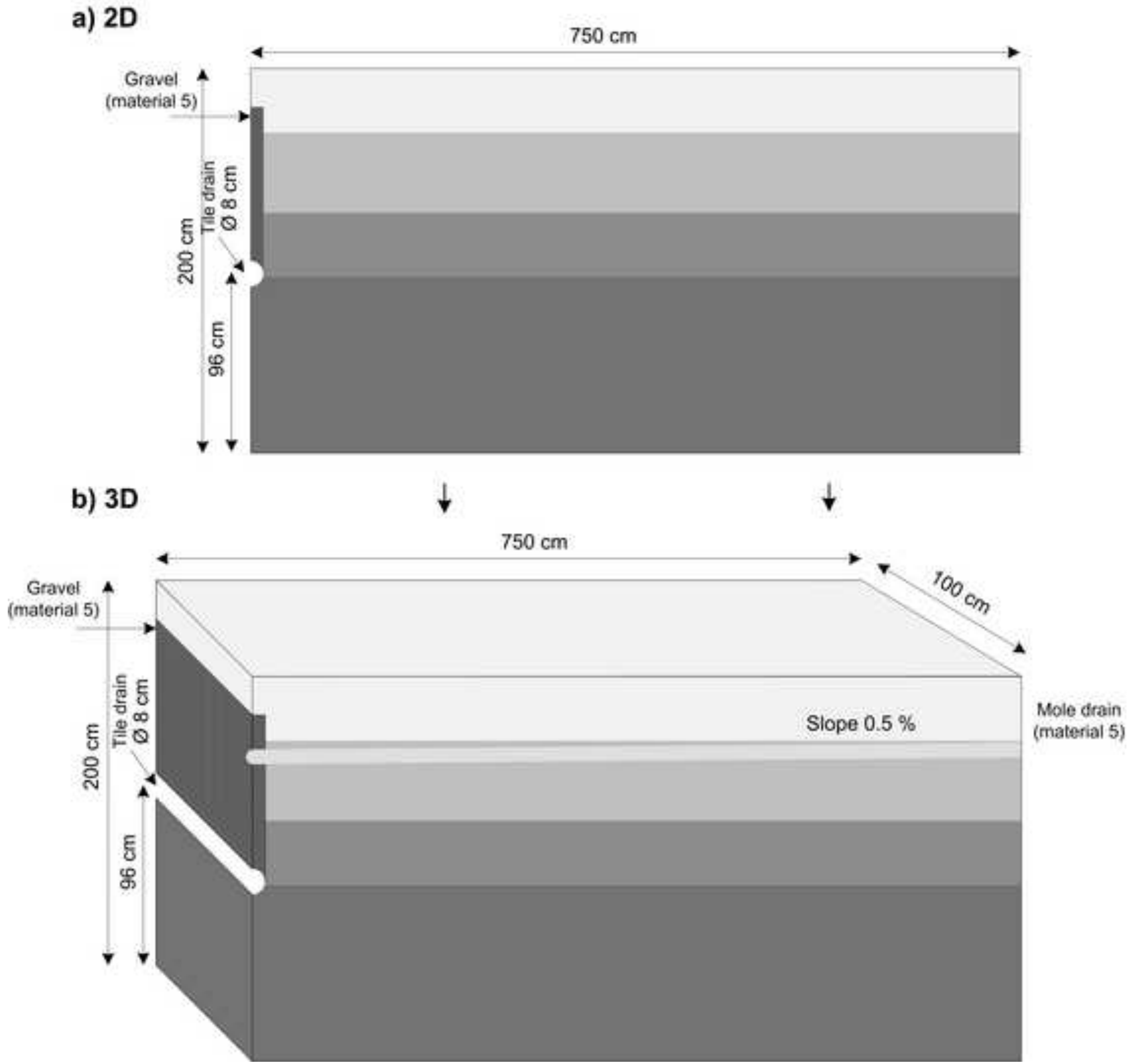
Material	**Depth (cm)**	θ_r **(cm^3 cm^{-3})**	θ_s **(cm^3 cm^{-3})**	α **(cm^{-1})**	n	K_s **(cm day^{-1})**	l
1	0-30	0.095	0.42	0.00136	1.20	12	0.5
2	30-70	0.095	0.41	0.00212	1.18	14	0.5
3	70-100	0.095	0.41	0.00136	1.20	12	0.5
4	100-200	0.102	0.50	0.0121	1.41	12.8	0.5
5	Gravel (trench and mole) material	0.005	0.42	0.1	2.1	3000	0.5

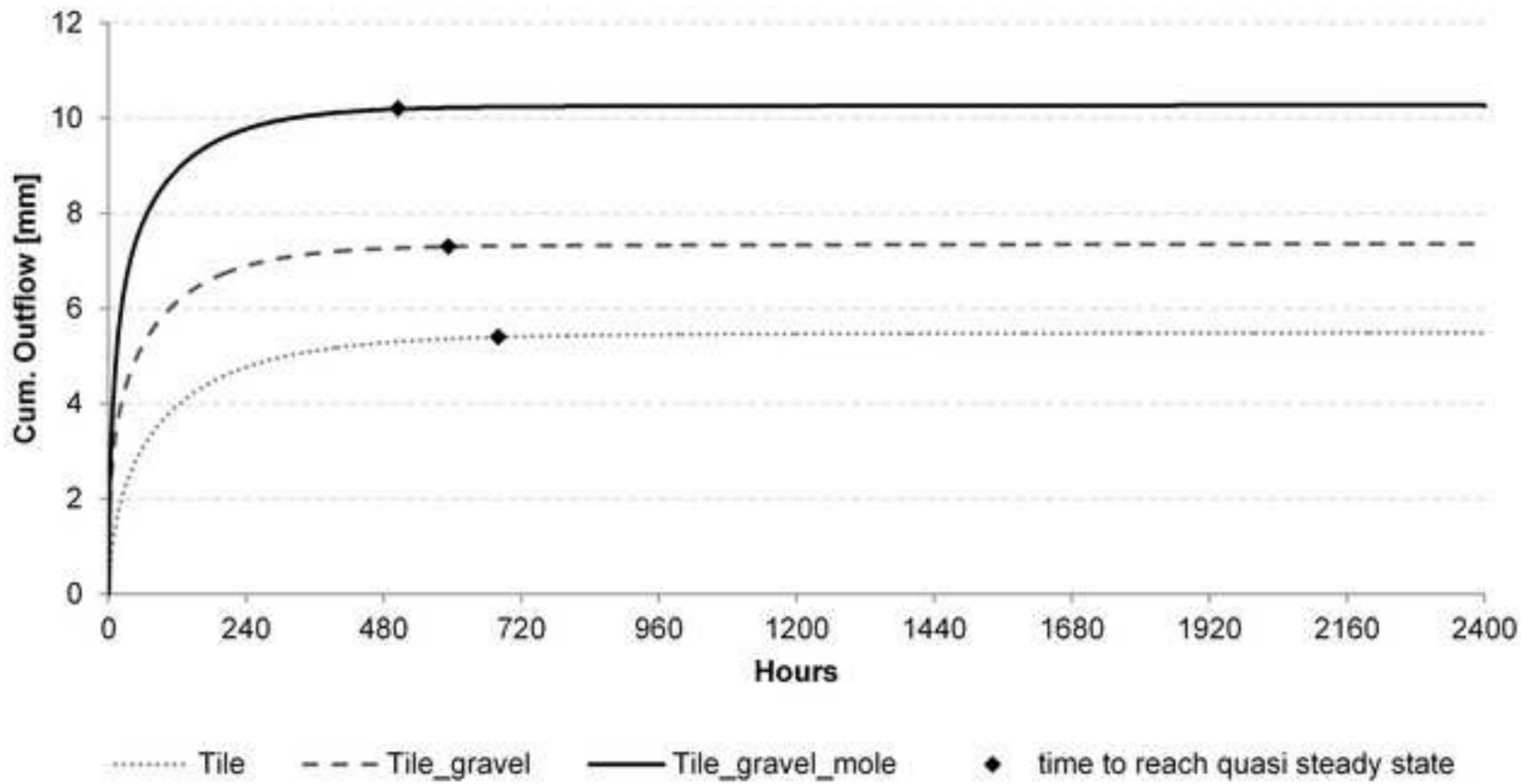
Table 2. Water balance (ΔWS – change in storage) for the various material layers composing the three simulated systems at the end of “time to drain” scenario (mm).

		All Materials	**Mat 1**	**Mat 2**	**Mat 3**	**Mat 4**	**Mat 5**
ΔWS in each system	**Tile**	-5.35	-1.12	-0.87	-0.68	-2.68	0.00
	Tile_gravel	-7.21	-1.14	-0.96	-0.72	-2.68	-1.71
	Tile_gravel_mole	-10.21	-1.14	-1.91	-0.72	-2.68	-3.76
Difference between the systems	**Tile vs Tile_gravel**	-1.86	-0.02	-0.09	-0.04	0.00	-1.71
	Tile vs Tile-gravel_mole	-4.86	-0.02	-1.04	-0.04	0.00	-3.76

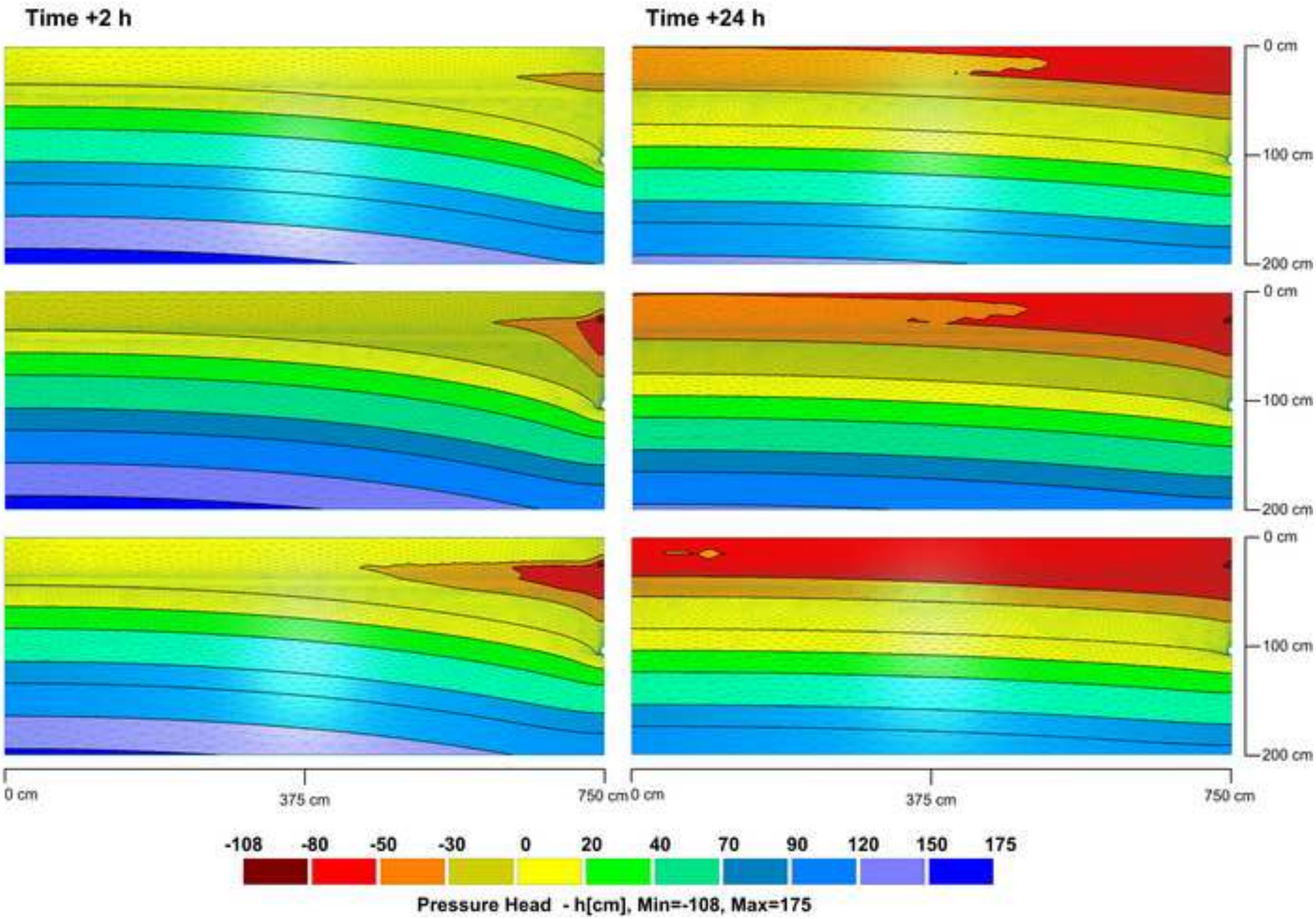
Table 3. Mass balance for all three simulated systems for scenario 2 – subscripts 50, 100, and 150 correspond to the cumulative rainfall amount (mm).

	System 1_{50}	System 2_{50}	System 3_{50}	System 1_{100}	System 2_{100}	System 3_{100}	System 1_{150}	System 2_{150}	System 3_{150}
Rainfall	50.00	50.00	50.00	100.00	100.00	100.00	150.00	150.00	150.00
Outflow	16.57	19.58	28.13	29.71	35.65	51.22	42.81	51.69	74.26
Runoff	31.93	29.69	6.36	68.66	63.52	13.61	105.39	97.35	20.85
ΔWS	1.49	0.72	15.51	1.63	0.83	35.18	1.79	0.96	54.89

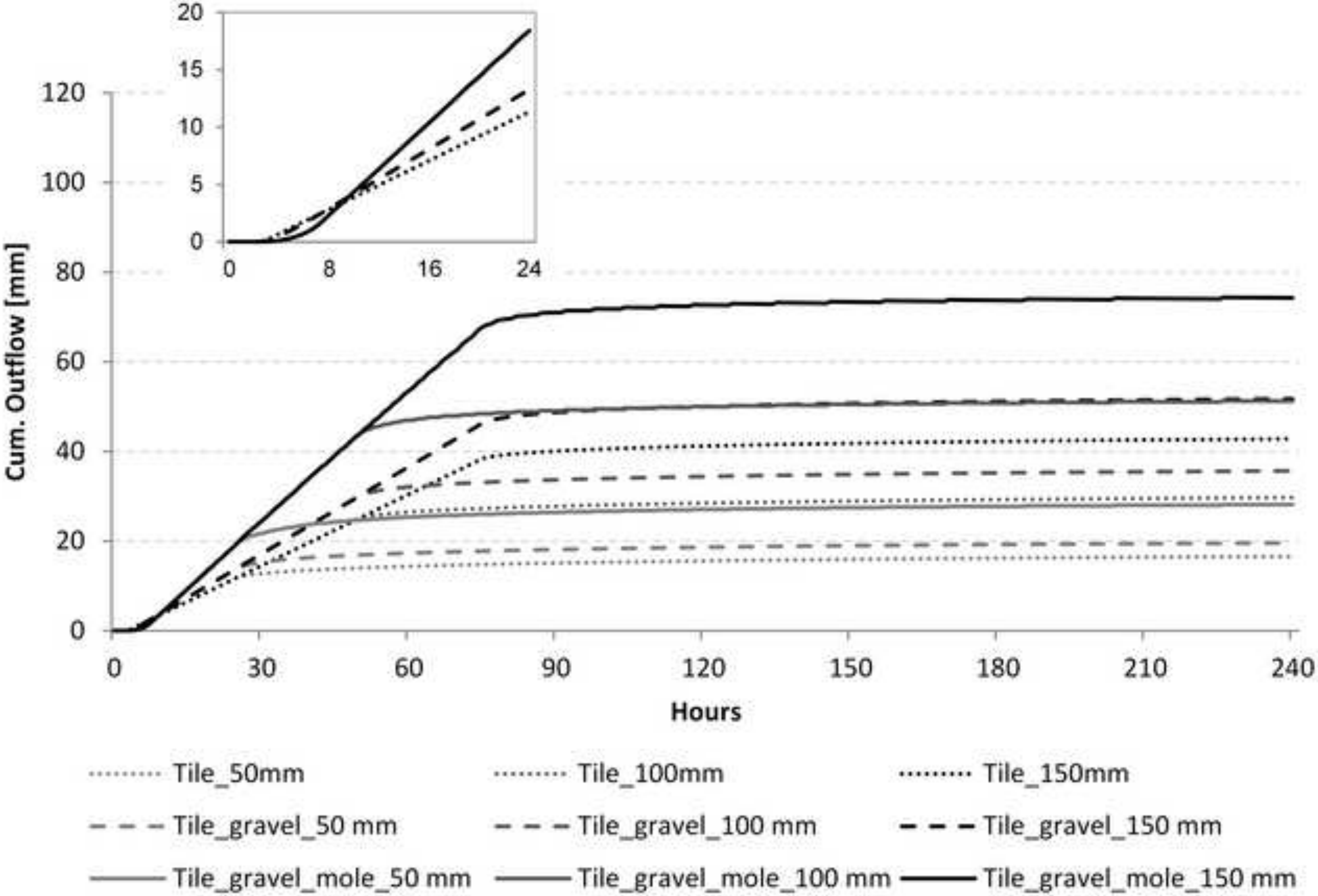

a) 2D
750 cm
Gravel
(material 5)
Tile drain
Ø 8 cm
200 cm
96 cm
b) 3D
750 cm
100 cm
Gravel
(material 5)
Tile drain
Ø 8 cm
200 cm
96 cm
Slope 0.5 %
Mole drain
(material 5)



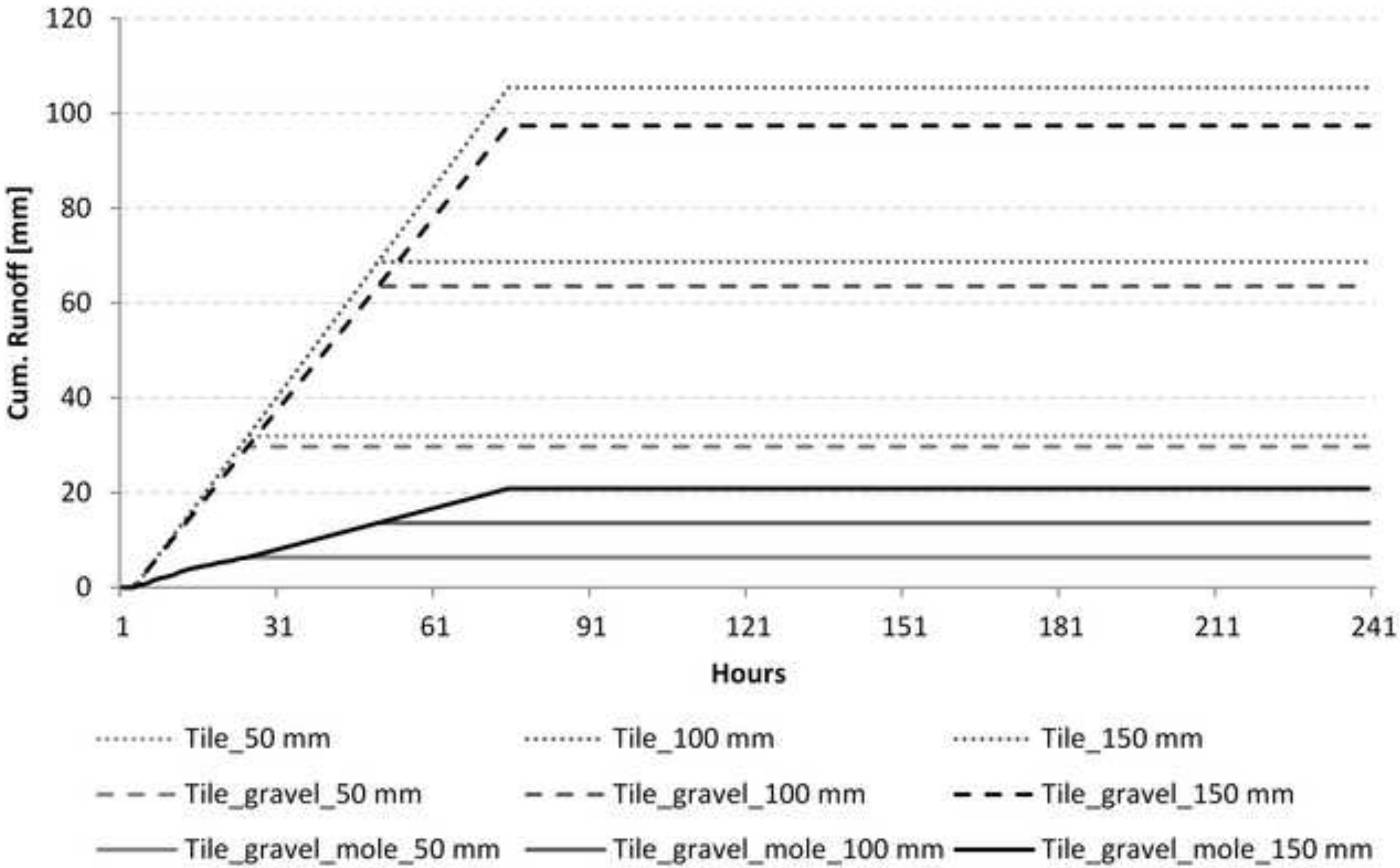
12
10
8
6
4
2
0
Cum. Outflow [mm]
0
240
480
720
960
1200
1440
1680
1920
2160
2400
Hours
Tile
Tile_gravel
Tile_gravel_mole
time to reach quasi steady state



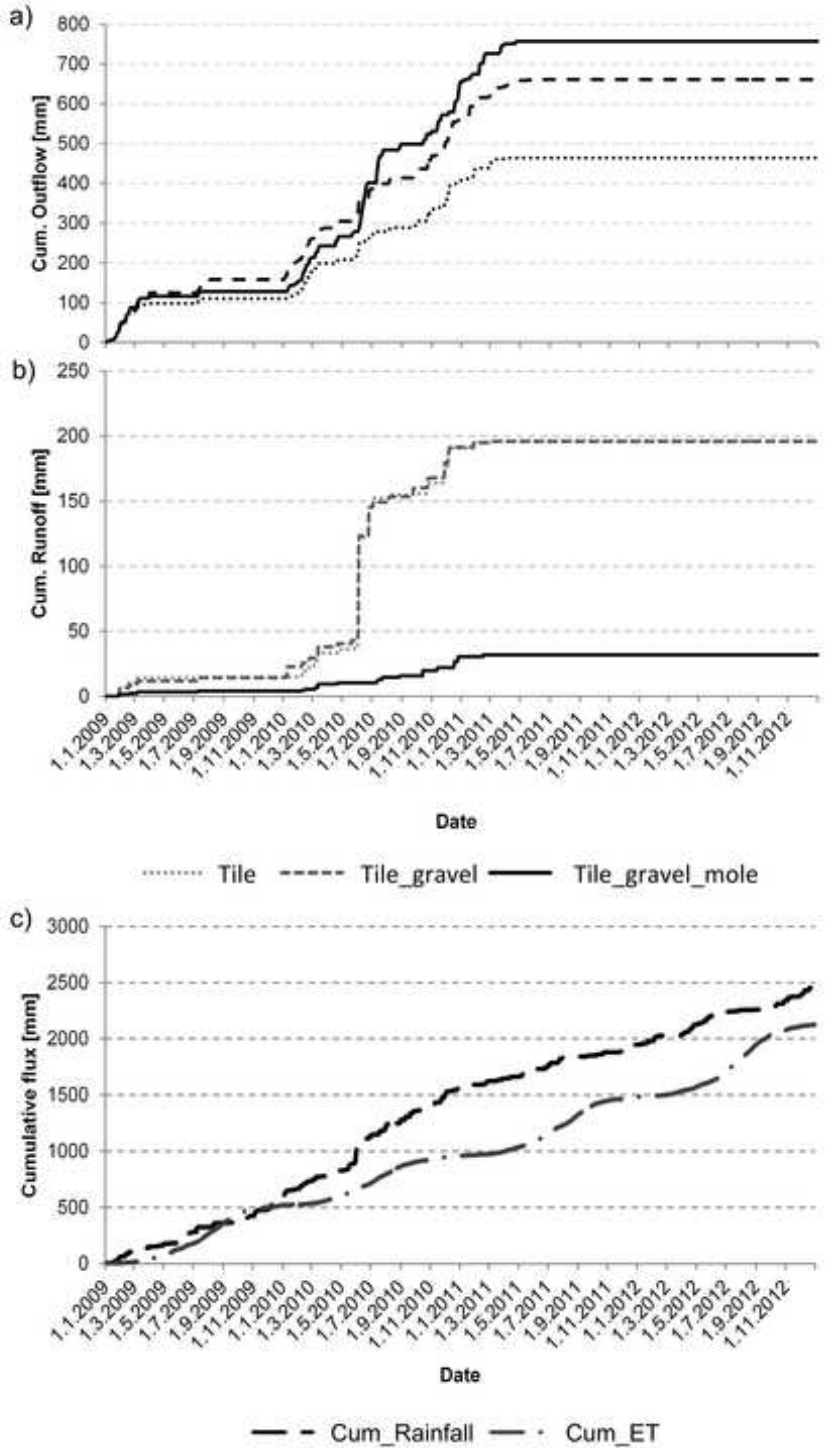
Time +2 h
Time +24 h
0 cm
100 cm
200 cm
0 cm
375 cm
750 cm
-108
-80
-50
-30
0
20
40
70
90
120
150
175
Pressure Head - h[cm], Min=-108, Max=175

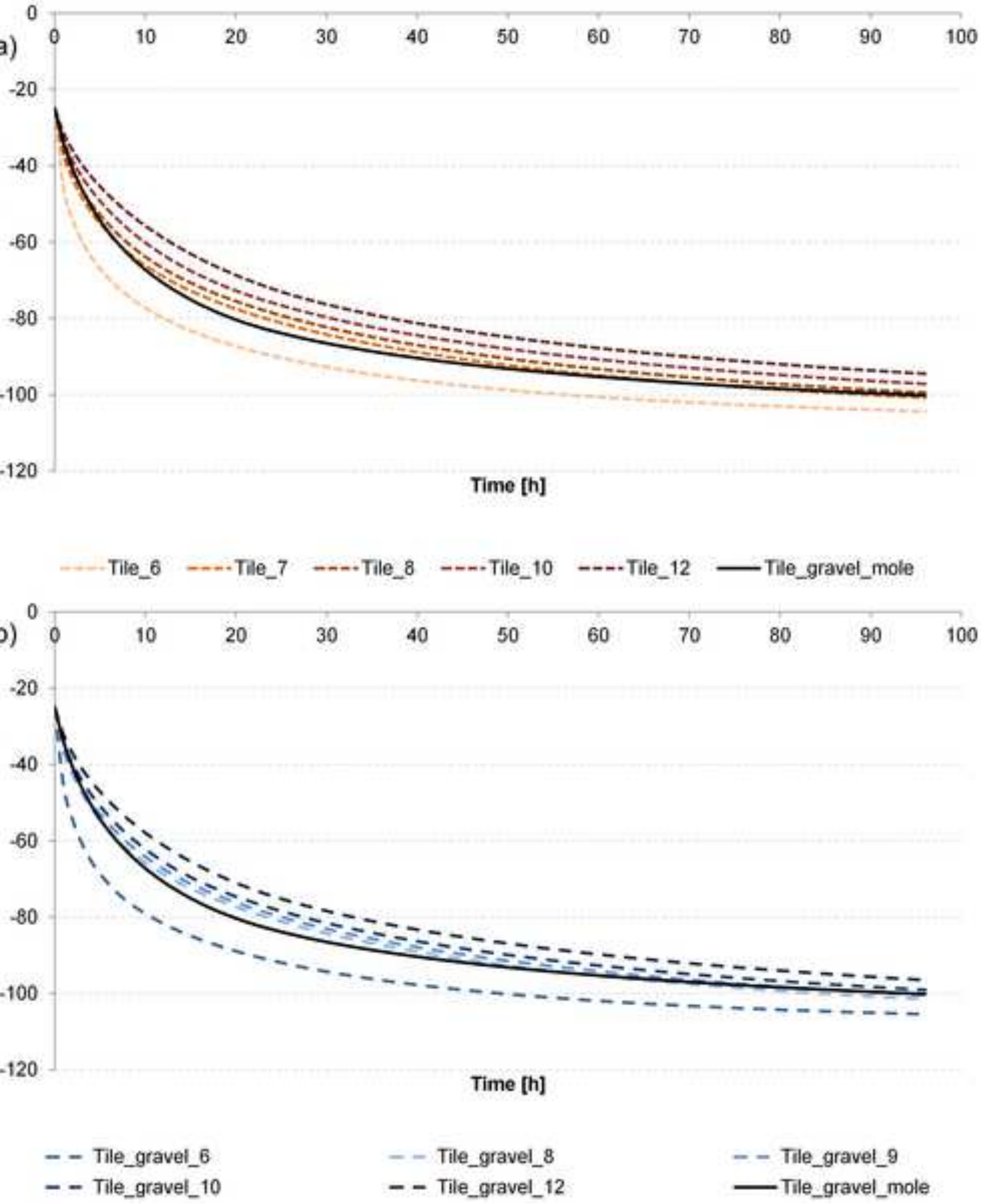


Cum. Outflow [mm]
Hours
0
20
40
60
80
100
120
0
30
60
90
120
150
180
210
240
0
5
10
15
20
0
8
16
24
Tile_50mm
Tile_100mm
Tile_150mm
Tile_gravel_50 mm
Tile_gravel_100 mm
Tile_gravel_150 mm
Tile_gravel_mole_50 mm
Tile_gravel_mole_100 mm
Tile_gravel_mole_150 mm



120
100
80
60
40
20
0
Cum. Runoff [mm]
1
31
61
91
121
151
181
211
241
Hours
Tile_50 mm
Tile_100 mm
Tile_150 mm
Tile_gravel_50 mm
Tile_gravel_100 mm
Tile_gravel_150 mm
Tile_gravel_mole_50 mm
Tile_gravel_mole_100 mm
Tile_gravel_mole_150 mm


a)
Cum. Outflow [mm]
0
100
200
300
400
500
600
700
800
b)
Cum. Runoff [mm]
0
50
100
150
200
250
1.1.2009
1.3.2009
1.5.2009
1.7.2009
1.9.2009
1.11.2009
1.1.2010
1.3.2010
1.5.2010
1.7.2010
1.9.2010
1.11.2010
1.1.2011
1.3.2011
1.5.2011
1.7.2011
1.9.2011
1.11.2011
1.1.2012
1.3.2012
1.5.2012
1.7.2012
1.9.2012
1.11.2012
Date
Tile
Tile_gravel
Tile_gravel_mole
c)
Cumulative flux [mm]
0
500
1000
1500
2000
2500
3000
1.1.2009
1.3.2009
1.5.2009
1.7.2009
1.9.2009
1.11.2009
1.1.2010
1.3.2010
1.5.2010
1.7.2010
1.9.2010
1.11.2010
1.1.2011
1.3.2011
1.5.2011
1.7.2011
1.9.2011
1.11.2011
1.1.2012
1.3.2012
1.5.2012
1.7.2012
1.9.2012
1.11.2012
Date
Cum_Rainfall
Cum_ET


a)
b)
0
-20
-40
-60
-80
-100
-120
0 10 20 30 40 50 60 70 80 90 100
Time [h]
Tile_6
Tile_7
Tile_8
Tile_10
Tile_12
Tile_gravel_mole
Tile_gravel_6
Tile_gravel_8
Tile_gravel_9
Tile_gravel_10
Tile_gravel_12
Tile_gravel_mole